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DESIGN AND IMPLEMENTATION OF SOFTWARE ALGORITHMS FOR TOPEX/POSEIDON ONBOARD EPHEMERIS REPRESENTATIONS*

R. K. Leavitt, Sterling Software, Inc.
A. H. Salama, Jet Propulsion Laboratory

Jet Propulsion Laboratory, California Institute of Technology
Pasadena, California

Abstract

The TOPEX/POSEIDON onboard computer (OB C) requires knowledge of the satellite and the Tracking Data and Relay Satellite (TDRSs) ephemerides to perform attitude control and high gain antenna (HG A) articulation. These ephemerides are uplinked to the satellite via the OB C Ephemeris Command Loads File, which is produced by program OBCGEN of the ground software Navigation Subsystem (NAVS). These OBC files are comprised of sets of coefficients and residuals for Fourier Power Series (FPS). Included are associated OBC flight times and the TOPEX satellite orbit ancl Earth spin rates. These FPS coefficients and auxiliary data are used by OBC to compute the ephemerides of the TOPEX satellite and TDRSS (East and West) as functions of satellite flight time.

Ephemeris files are produced by NAVS program DPTRAJ for the TOPEX satellite and each TDRS. For input, DPTRAJ uses solution vectors of the orbit determination (OD) process as initial states supplied by the Flight Dynamics Facility (FDF) at the Goddard Space Flight Center (GSFC). To conserve OBC memory, OBCGEN compresses each of these ephemerides into FPS representation while satisfying altimeter and HGA pointing accuracy requirements. A power series is computed spanning 10 days to represent each Cartesian position and velocity component of the satellite in true equator and equinox of date (TOD) coordinates. The. position components of both TDRS are represented in each uplink load.

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The TOPEX/POSEIDON OBC ephemeris representation is based on the FPS equations inherited from LA ND SAT-D (Ref 1), which invoked daily uploads spanning 37 hours each. Analysis has determined that the accuracy requirements for TOPEX/POSEIDON would be satisfied if the FPS equation domain was extended to weekly uplinks spanning 10 days (Ref 2). Modifications to OBC were necessary to accomplish this extension. The 37 hour clock was increased to 12,4 days, and the software logic was changed to allow a new range of coefficient values. A parameter was added to the uplinked file to indicate the user specified starting grid point for position residuals (spanning 30 hours at 10-min centers).

The satellite can enter a safehold mode if the ephemeris loads contain errors which cause unacceptably large pointing errors. Normal operations cease until a corrected ephemeris is uplinked. Several quality assurance steps are included in the command load generation process to reduce the possibility of uplinking a faulty ephemeris. The major quality assurance step within the OBCGEN program set is the "Verify OB C Ephemeris" process shown in fig. 2. Here, the intended OB C command loads are used to generate ephemerides (both TOPEX and each TDRS) using actual onboard algorithms. The resulting ephemerides are compared with the original ephemerides to confirm that differences are within acceptable limits. Residual plots, like those shown in Fig. 1, are but one part of this thorough verification process. Fig. 1 shows a typical maximum representation error of 6 mdeg, compared to the allocated error of 22 mdeg.

Figure 2 is a systems flow chart that illustrates the generation of the OBC Ephemeris Command Loads. In addition to ephemeris files, inputs include general information (GIN) and planetary ephemeris files. These files supply the parameters for polar motion and timing and the nutations in ecliptic longitude ant] obliquity, respectively. To relate flight software time with UTC, OBCGEN interfaces with a Time Correlation Table supplied by the Satellite Performance Analysis Team (SPAT). Along with the satellite coefficients is an opt ion for position residuals that span a user selected 30-hour period at 10 minute centers for greater precision during critical events. The resulting FPS coefficients are scaled and converted to their equivalent 18-bit word octal representation by emulating the numerical algorithms used by OBC. Verification of the uplinked FPS coefficients is accomplished by comparing functional values with the respect ive DPTRAJ ephemeris values. The command syntax of the OBCGEN Ephemeris Command Loads file is validated by SPAT and the file is uplinked to the satellite by the Telemetry, Command, and Communications Subsystem (TCCS).

For the TOPEX satellite, the form of these equations used to represent the ephemeris is a 5th degree least squares polynomial with FPS harmonic coefficients. Each Cartesian position and velocity component is represented with the following equation (Ref. 1):

$$
\begin{aligned}
x(t) = {} & A1 + tA_2 + t[A_3 + t(A_4 + t(A_5 + tA_6))] \\
& + A7 + t[A_8 + t(A_9 + t(A_{10} + t(A_{11} + tA_{12})))] \, sin(\omega t) \\
& + A_{13} + t[A_{14} + t(A_{15} + t(A_{16} + t(A_{17} + tA_{18})))] \, cos(\omega t) \\
& + A_{19} + t[A_{20} + t(A_{21} + (A22 + tA_{23}))] \, sin^2(\omega t) \\
& + A24 + t[A_{25} + t(A_{26} + t(A_{27} + tA_{28}))] \, sin(\omega t) \, cos(\omega t) \\
& + A29 + t[A_{30} + t(A_{31} + tA_{32})] \, sin^3(\omega t) \\
& + A33 + t[A_{34} + t(A_{35} + tA_{36})] \, sin^2(\omega t) \, cos(\omega t) \\
& + [A37 + A39 \, sin(\omega t) + A41 \, cos(\omega t)] \, sin(2\omega_E t) \\
& + [A_{38} + A_{40} \, sin(\omega t) + A_{42} \, cos(\omega t)] \, cos(2\omega_E t)
\end{aligned}
$$

where:

$x(t)$ is any of the six cartesian position or velocity components of the inertial coordinate system;
t is the OBC flight software time relative to the reference time for the ephemeris data span;
ω is the mean orbital frequency of the satellite for the data span;
$A_i (i=1,...,42)$ are the FPS harmonic coefficients, and
ω_E is Earth's sideral rotation frequency.

The satellite mean orbital frequency for the data span is computed from the mean semi-major axis obtained from orbit determination.

For TDRSS, each cartesian position (both east and west) component is represented with the following equation (Ref. 1):

$$
\begin{aligned}
x(t) = {} & A1 + A_2 t + (A_3 + tA_4) \, sin^2 \omega_E t \\
& + (A_5 + tA_6) \, cos \, \omega_E t + A7 \, sin^2 \omega_E t \\
& + A8 \, sin \, \omega_E t \, cos \, \omega_E t
\end{aligned}
$$

where each position component is determined from eight coefficients. parameter ω_E is Earth's sideral rotation frequency.

The ephemerides are reconstructed in OBC by interpolating over grid points at 10 minute centers. The grid points are computed using the uplinked FP S coefficients, and the OB C interpolation algorithm applies the following Hermite formula (Ref. 2):

$$
\begin{aligned}
y(t) &= \sum_{k=0}^{m} h_k(t) f(t_k) + \sum_{k=1}^{m} H_k(t) f'(t_k) \\
h_k(t) &= [1 - 2L'_k(t_k)(t - t_k)][L_k(t)]^2 \\
H_k(t) &= (t - t_k)[L_k(t)]^2
\end{aligned}
$$

where:
$y(t)$ is the Hermite polynomial of degree $2m - 1$, representing any position or velocity component,
m is the number of points used in the interpolation,
$f(t_k)$ and $f'(t_k)$ are any position and corresponding velocity components, and
$L_k(t)$ and $L'_k(t)$ are the Lagrangian coefficient functions and their derivatives.

The least squares normal equation (Ref. 3) is applied by OBCGEN to approximate ephemerides. This equation can be expressed as follows:

$$\left(\sum_{i=1}^{p} \underline{t}_i \underline{t}_i^T\right) C = \sum_{i=1}^{p} \underline{t}_i X_i^T$$

where p is the number of ephemeris points, X_i is the i^{th} DPTRAJ ephemeris vector of Cartesian position and velocity components, and C is the estimated 42×6 array of coefficient. Vector $\underline{t}_i$ is defined at time t_i, i = 1, ... p, by partitioning it into harmonic factor segments as follows:

Let

$$q_i^n = \begin{pmatrix} 1 \\ t_i \\ \cdot\ \cdot \\ t_i^n \end{pmatrix}$$

then

$$\underline{t}_i = \begin{pmatrix} q_i^5 \\ q_i^5 \sin \omega t_i \\ q_i^5 \cos \omega t_i \\ q_i^4 \sin^2 \omega t_i \\ q_i^4 \sin \omega t_i \cos \omega t_i \\ q_i^3 \text{ sin } \sin^3 \omega t_i \\ q_i^3 \sin^2 \omega t_i \cos \omega t_i \\ E_i \end{pmatrix}$$

where

$$E_i = \begin{pmatrix} \sin \omega_E t_i \\ \cos \omega_E t_i \\ \sin \omega_E t_i \sin \omega t_i \\ \cos \omega_E t_i \sin \omega t_i \\ \sin \omega_E t_i \cos \omega t_i \\ \cos \omega_E t_i \sin \omega t_i \end{pmatrix}$$

The time values t used in the least squares equation are scaled quantities representing OBC flight times. They are scaled so that their values lie between – 1 and +1 as follows:

$$t = \frac{t_s - t_o}{\text{At}}$$

where

$$t_s = \text{OBC flight time}, \; t_1 \leq t_s \leq t_p$$

$$t_o = \frac{t_1 + t_p}{2}$$

$$\text{At} = \frac{t_p - t_1}{2}$$

The value t_o is called the reference time, and Δt, the scaling factor, is the interval between t_1 and t_o. In reconstructing the ephemeris, OBC is required to subtract t_o from OBC flight times in applying the coefficients, i.e., $t = t_s - t_o$. However, At is factored into the uplinked coefficients A_n by OBC G EN as follows:

$$A_n = \frac{C_n}{\Delta t^n} \quad , \text{ for } n = 1, \ldots, 5$$

where C_n are the least squares computed coefficients for the n^{th} power of t.

Three time values are incorporated into the OBC Ephemeris Command Loads File, viz., t_{START}, t_{USE}, and At. The time t_{START} signals OBC to compute the first four ephemeris grid points from the associated coefficients. Time t_{USE}, which coincides with the second grid point, identifies when OBC initiates the interpolation process using these grid points. The time interval At is the time between the first grid point and the reference time, i.e.,

$$t_o = t_1 - At$$

Since the grid points are on 10 minute, i.e., 600 second, centers,

$$t_1 = t_{USE} - 600.$$

The measuring units used by OBCGEN in the least squares process are kilometers and seconds to be consistent with DPTRAJ ephemeris files. These units must be converted to OB C units, viz., meters and milliseconds, for the OB C Ephemeris Command Loads File to be uplinked to the satellite.

Scale factors similar to the exponent in floating point numbers are stored in the OBC memory, These scale factors position the logical binary point for the System Table "real" parameters by multiplying by 2^n, where n is the scale factor. Since the hardware binary point is at the left of the most significant bit position, the stalling factor logically moves the point n bit position to the right (to the left if $n < 0$),

Scale factors for TOPEX/POSEIDON were optimized for FPS coefficients providing a 10-day ephemeris representation. Experience has shown that numerical problems sometimes occur when these scale factors were used to generate ephemerides less than 6 days (near maneuvers, for example). Underflow and loss of the most significant bit occurs because the scale factors no longer accommodate the required FPS coefficients. As a result, a standardized 10-day ephemeris is always utilized regardless of the mission activity, since it is operationally impractical to also determine and uplink new scale factors with each ephemeris command load,

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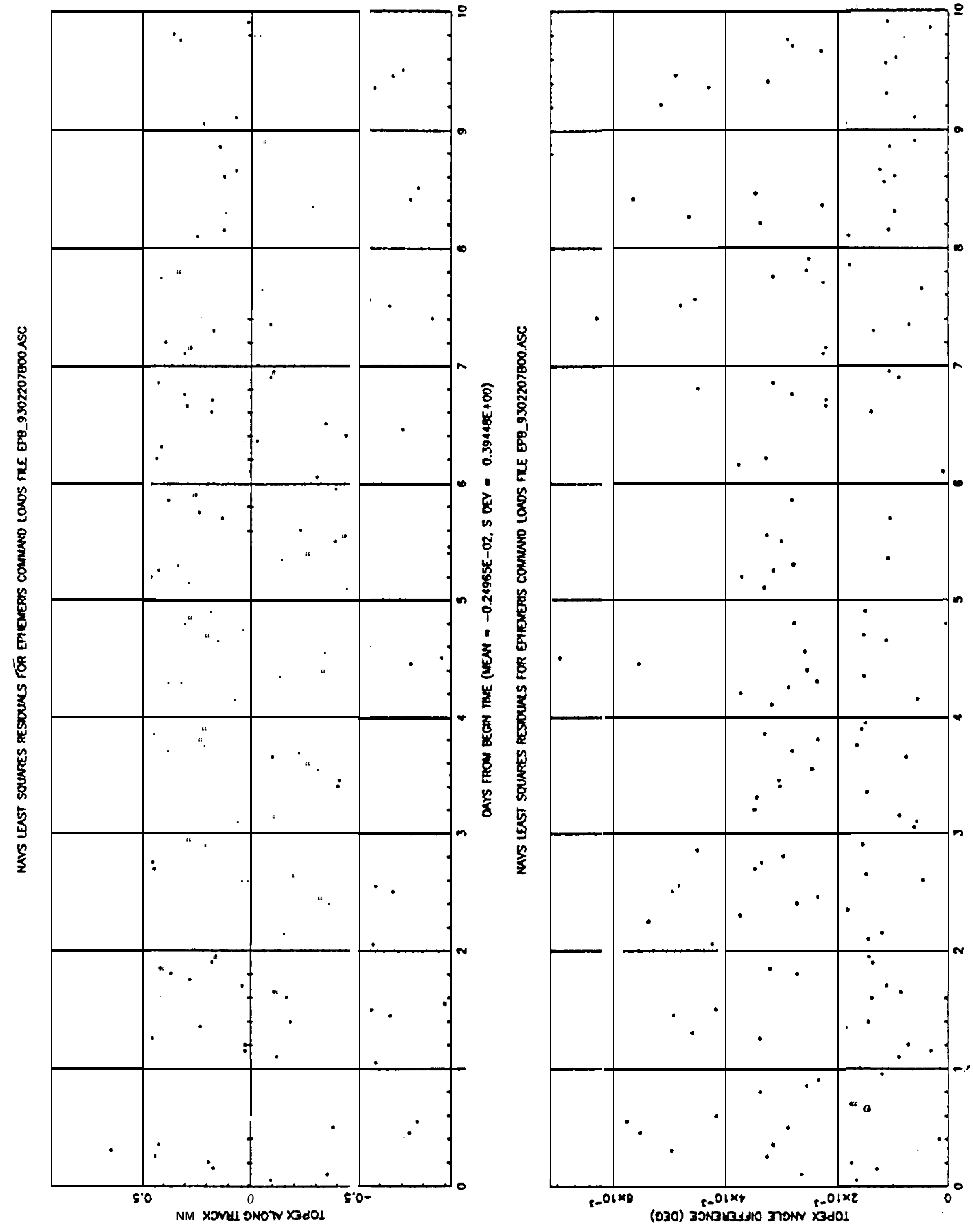

Figure 1. Pointing Error Verification

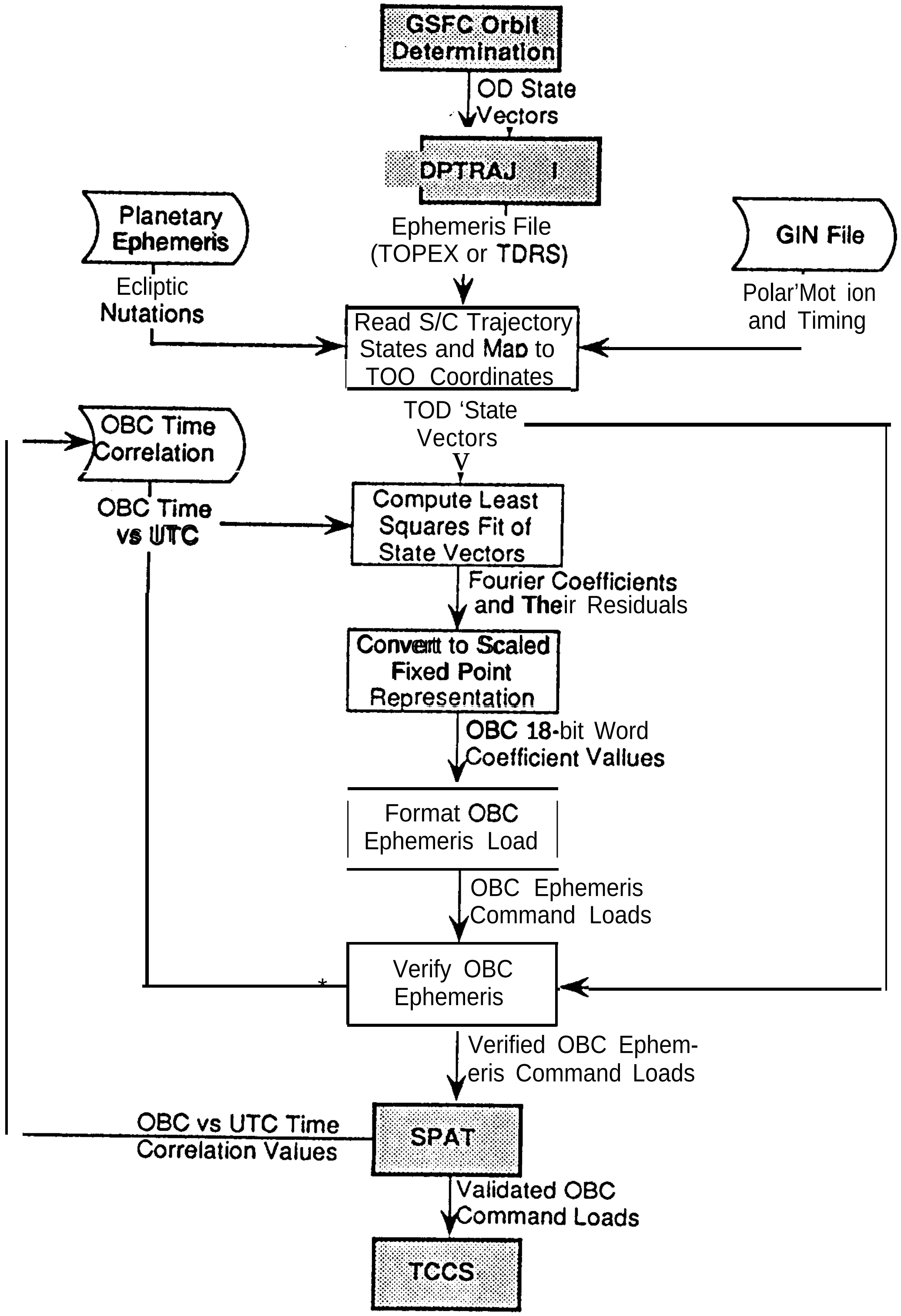

Figure 2. OBCGEN System Flow Chart